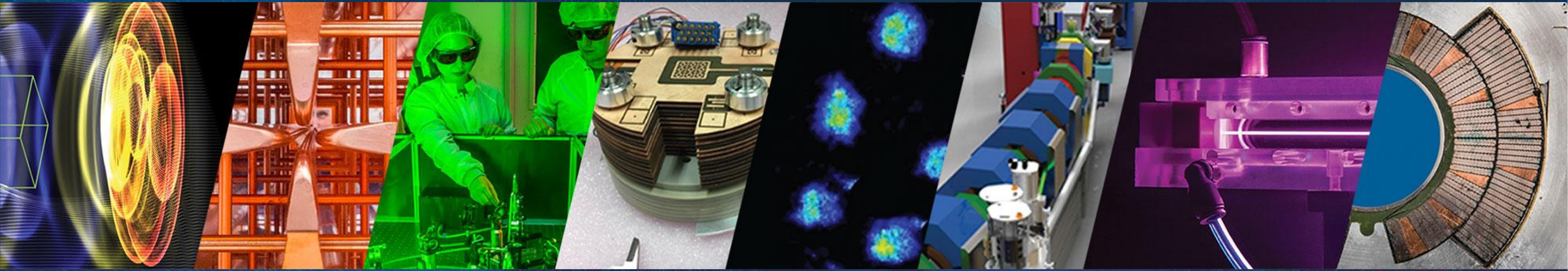
Update on Activities and Capabilities at LBNL

Steve Gourlay
Accelerator Technology & Applied Physics Division



INFUSE Workshop, October 19, 2022

BERKELEY LAB

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

U.S. DEPARTMENT OF ENERGY | Office of Science

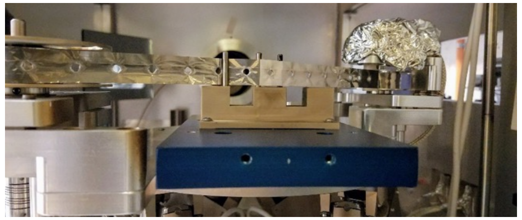
LBNL Offers Core Capabilities to Advance the FES Plan

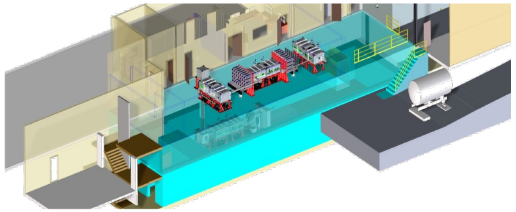
ATAP Programs

- Berkeley Center for Magnet Technology
- US Magnet Development Program
- Fusion Sci. & Ion Beam Technology Program
- Berkeley Lab Laser Accelerator (BELLA) Center
- Advanced Light Source Accelerator Physics
- Accelerator Modeling Program
- Berkeley Accelerator Controls & Instrumentation Program

- Capabilities in priority areas addressing the FES Long Range Plan
  - Magnet and fusion R&D
  - LaserNetUS user and collaborative science
  - High Energy Density Physics
  - Quantum Information Science

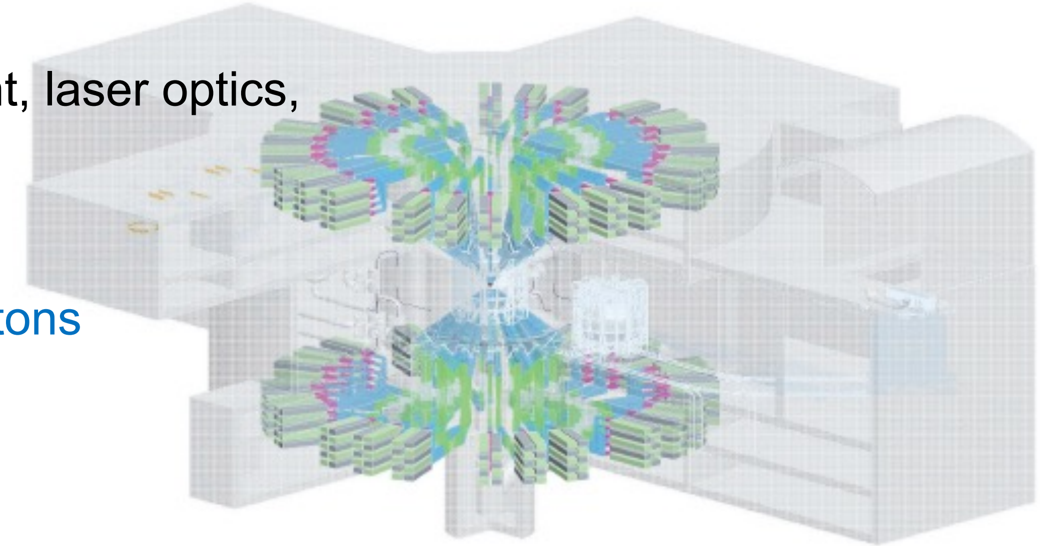
- Leveraging context of excellence in Computing, Lasers, Magnets, Engineering, and Quantum at LBNL and UC Berkeley





Opportunities for fusion relevant research in ATAP

- Laser acceleration of protons for fast ignition
  - Upgrades of PW laser: pulse shaping, contrast improvement, laser optics, active feedback, etc.
  - Advanced targets to enhance energy coupling to protons
  - Rep-rated (1 Hz) targets and diagnostics
- Ultrafast probes from laser-plasma sources of particles and photons
  - Improve source performance: flux and stability
  - Timing and synchronization
  - Participate in experiments through LaserNetUS
- Exascale computation
  - PIC modeling, development for new architectures
  - Hydrodynamic modeling of plasmas on long time scales (1-100 ns)
  - Transition from macro (structured solids) to the micro (plasmas)
- Novel ion acceleration techniques based on MEMS
  - R&D on efficient ion accelerators for material studies and future IFE drivers
  - Heavy Ion Fusion
- Lasers based on coherent combination of fibers
  - High efficiency high average power lasers



High Field Magnet Leadership for Compact Fusion Plants

- **Field is key to device size: High Temperature Superconductors (HTS) have potential for 2x field**
- **LBNL leads High Energy Physics US Magnet Development Program – Leverage for fusion**
  - Started: FES Test Facility Dipole + commercial partnerships (Commonwealth, General Atomics…)
  - Goal: lead program from cable to diagnostics to advanced HTS magnets to support pilot plant

FES Magnet Program @ LBNL

Understand and mitigate the degradation in HTS fusion cables → Design and develop technologies for robust fusion magnet systems → Enable the next FES facility

Advanced diagnostics

Demountable joints

Radiation effects

Other emerging needs, e.g., system-level protection

Vision:
Leverage BCMT expertise, experience, and community reputation to organize and steer the superconductor and superconducting magnet community to deliver on the FES Long Range Plan for fusion power

Cable and magnet R&D

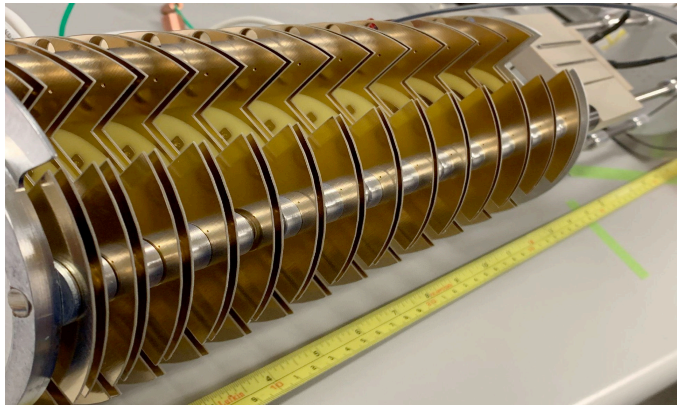
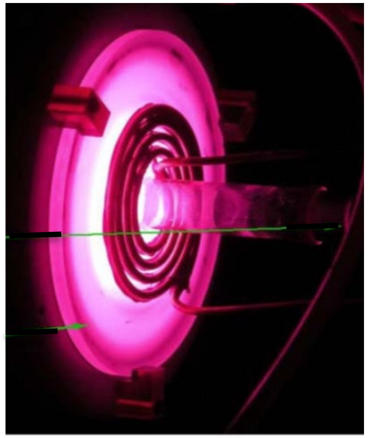
Enabling R&D

Contact: Soren Prestemon
soprestemon@lbl.gov

Ion beams for neutral beam injectors and new applications of intense ion beams

- LBNL has developed ion beams for neutral beam injectors and plasma heating back in the 1980s and we are active today in the development of novel high power ion beams
- We have expertise with positive and negative ions
- A test stand with a 150 kV injector is available e. g. for neutral beam injector R&D
- We have developed a new RF ion linac architecture based on stacks of low-cost wafers
- These ion accelerators now enable new applications of low cost, compact and modular ion beams, e. g. for plasma diagnostics and fusion materials studies with ions and ion driven neutron sources

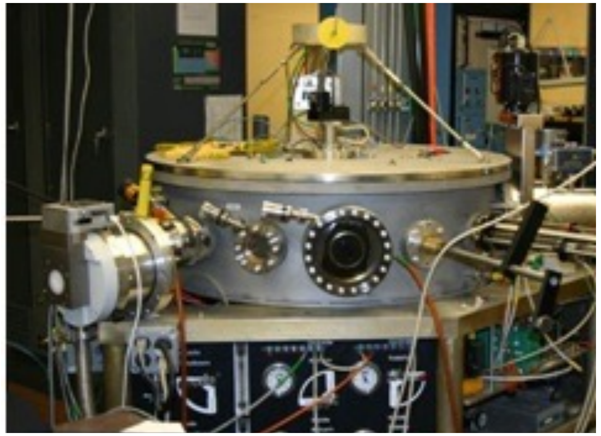

- Photo of the 150 kV injector with R&D ion beamline

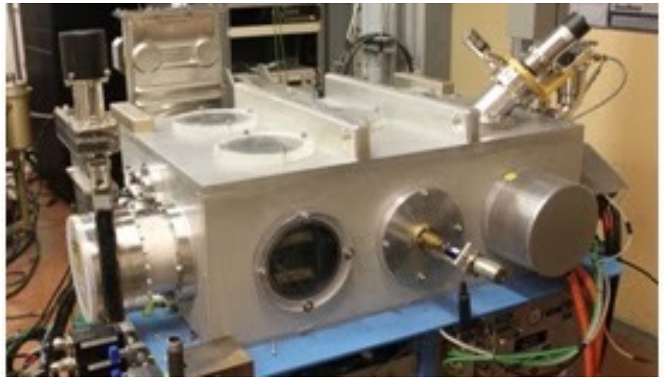



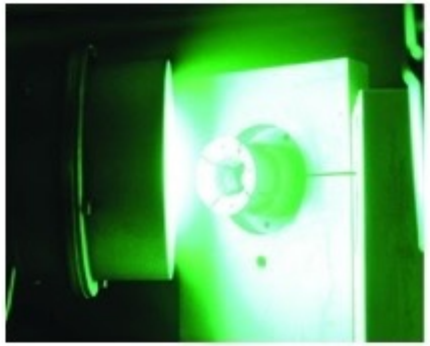
- Photos of a multi-beam RF linac for 110 keV ions (left), and an RF driven ion source with external antenna
- Q. Ji, et al., Rev. Sci. Inst. 92, 103301 (2021)

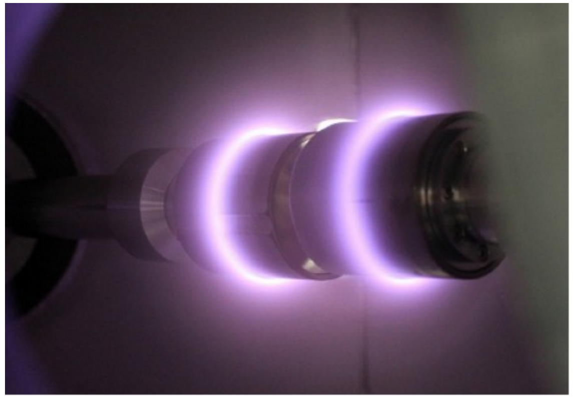
- Contacts: Thomas Schenkel, Qing Ji, Arun Persaud
  - T_Schenkel@LBL.gov, Qji@LBL.gov, APersaud@LBL.gov

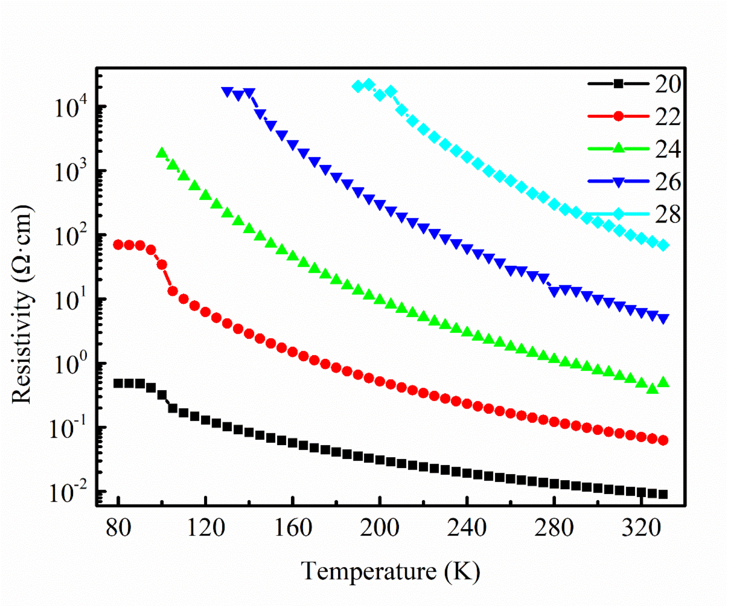
We have high power magnetron and cathodic arc plasma coating capabilities – an application example is quench protection of REBCO cables







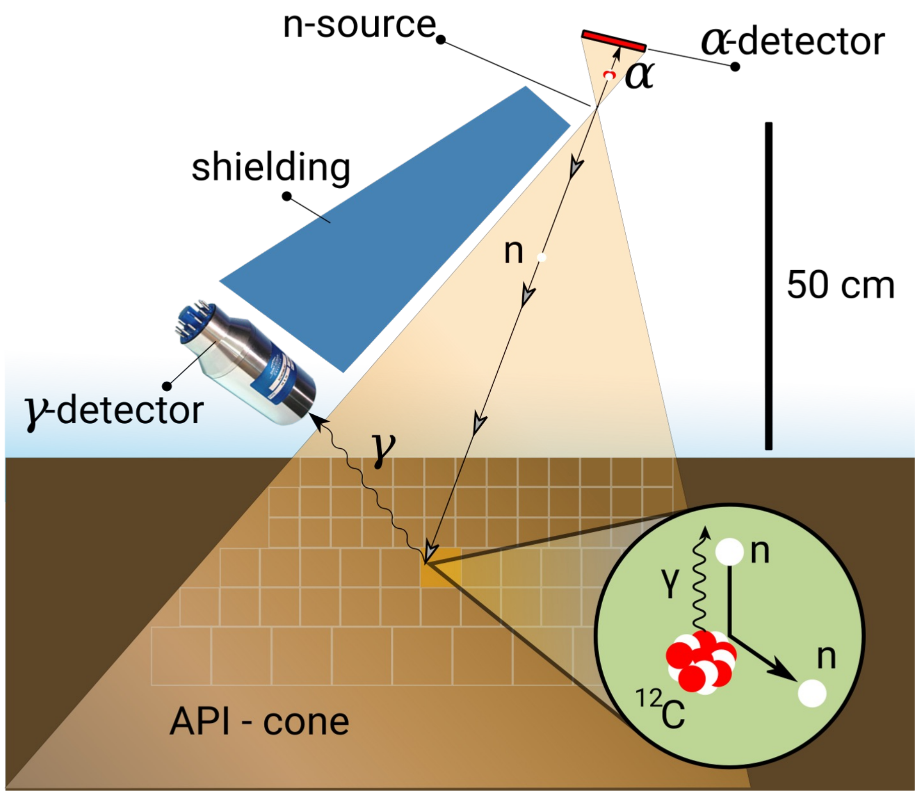


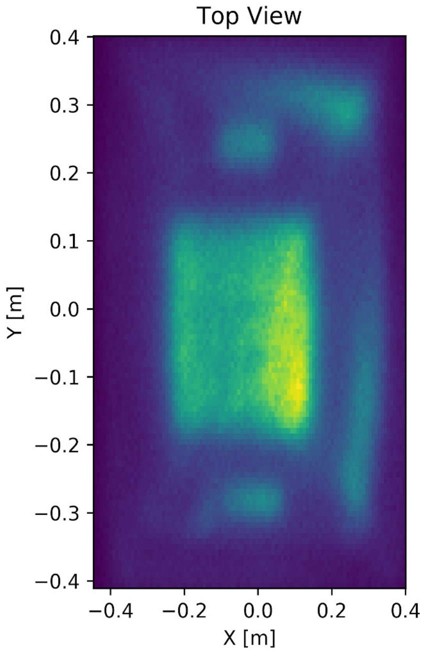


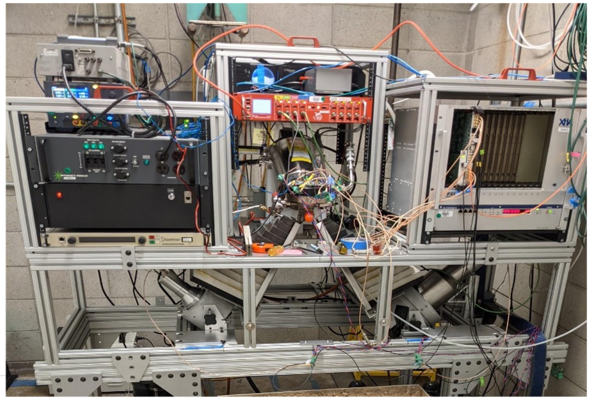
- Hall effect measurements show that the resistivity of VO_x films at room temperature was at least 3 orders of magnitude lower than at 77 K.
- Z. Yang et al, "Vanadium oxide coatings to self-regulate current sharing in high-temperature superconducting cables and magnets", Journal of Applied Physics 128, 055105 (2020)

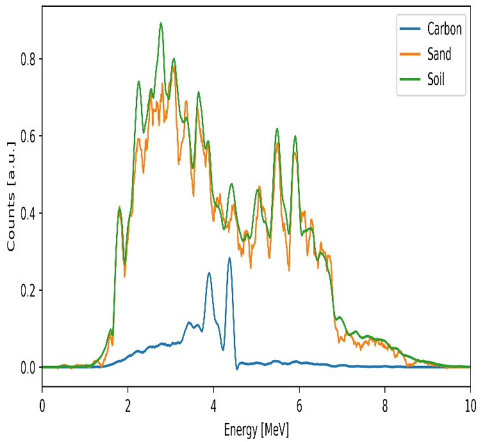
- Contacts: Qing Ji, Qji@LBL.gov

We have neutron based elemental imaging capabilities that can be applied to fusion materials characterization









- Photo of the DT neutron generator setup with gamma detectors and coincidence electronics in a shielded hutch, and examples of gamma spectra and images of carbon distributions in soil

- Contact: Arun Persaud, APersaud@LBL.gov
- A. Unzueta Mauricio, et al., "An all-digital associated particle imaging system for the 3D determination of isotopic distributions", Rev. Sci. Instrum. 92, 063305 (2021), https://doi.org/10.1063/5.0030499

ECP WarpX code is relevant to many fusion and plasma physics topics

WarpX

ECP EXASCALE COMPUTING PROJECT

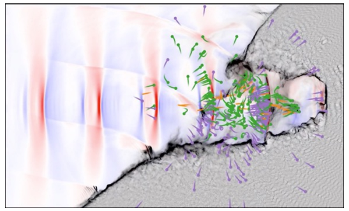
- WarpX is **an advanced Particle-In-Cell code**
- Fully **open-source** & **documented**
  `github.com/ECP-WarpX/WarpX`
  `warpx.readthedocs.io`
- Runs on largest **CPU or GPU-based supercomputers**, as well as on single-user laptops or desktop

- Large team of contributors from worldwide institutions

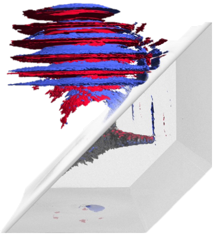
BERKELEY LAB | Lawrence Livermore National Laboratory | SLAC | cea PARIS-SACLAY | DESY. | CERN

Many fusion-relevant features in WarpX

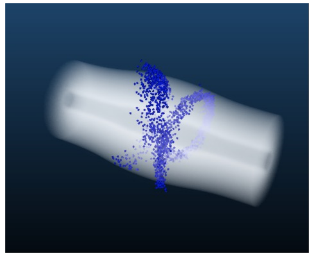
- Full support for **laser-plasma** interactions
- Monte-Carlo modules for:
  - fusion reactions
  - Coulomb collisions
  - ionization physics
  - …



- Support for arbitrarily-shaped **metallic boundaries** (e.g., from STL files)

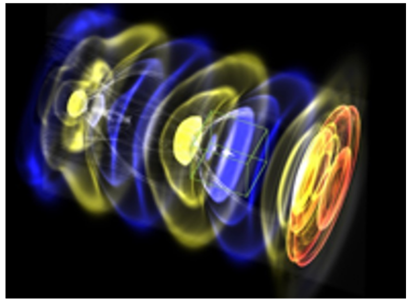


- **Python interface** allows coupling with **custom user code/modules**.



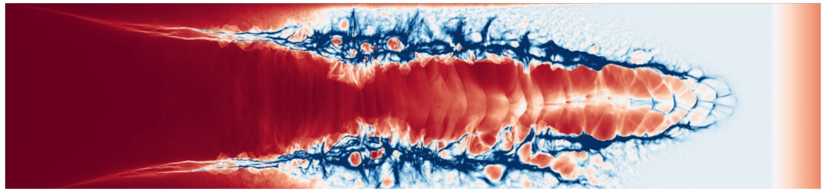
Contact: Jean-Luc Vay (LBNL, jlvay@lbl.gov)

WarpX supports a growing number of applications

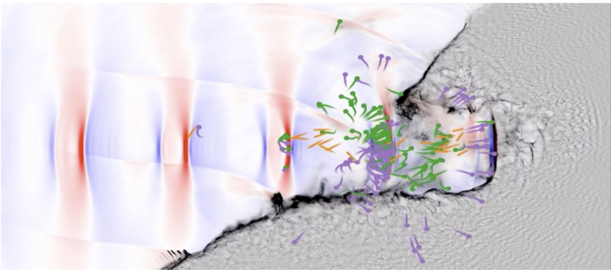


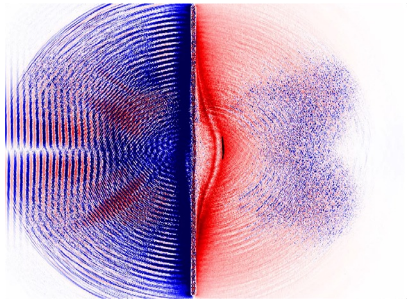
Plasma accelerators (LBNL, DESY, SLAC)

Laser-ion acceleration - advanced mechanisms (LBNL)



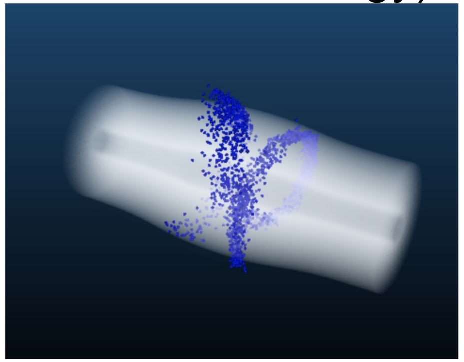
Plasma mirrors and high-field physics + QED (CEA Saclay/LBNL)



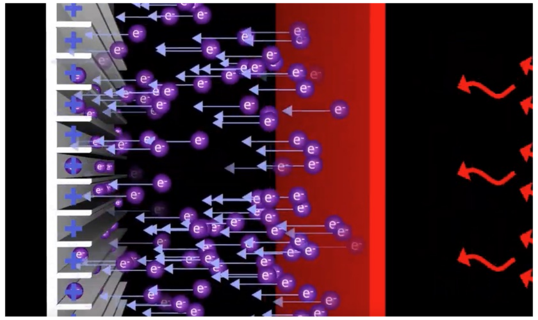


Laser-ion acceleration - laser pulse shaping (LLNL)

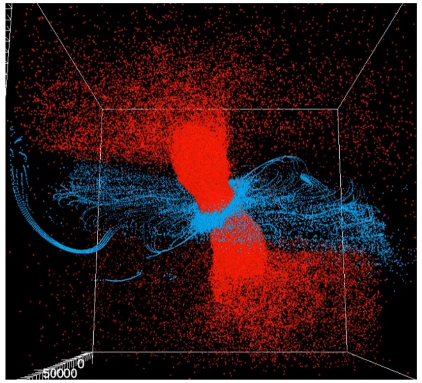
Plasma confinement, fusion devices (Zap Energy, Avalanche Energy)



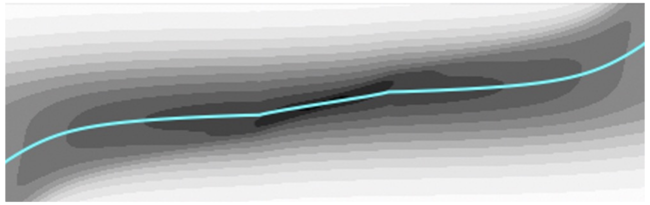
Thermionic converter (Modern Electron)



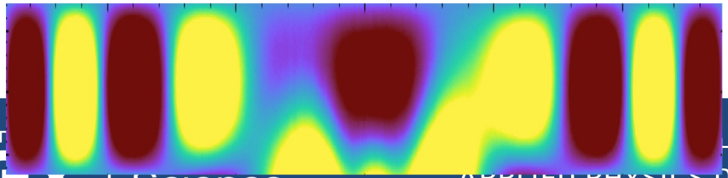
Pulsars, magnetic reconnection (LBNL)

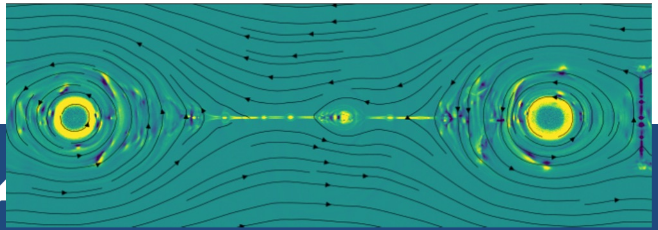


Magnetic fusion sheaths (LLNL)

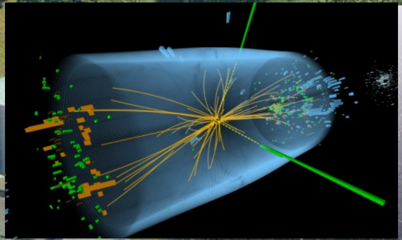


Microelectronics (LBNL) - ARTEMIS





BELLA Center houses multiple laser facilities, each addressing laser, accelerator, and light source R&D and applications

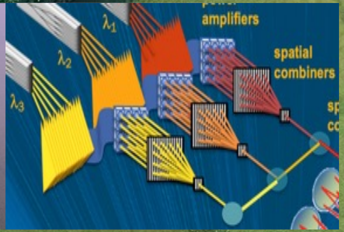


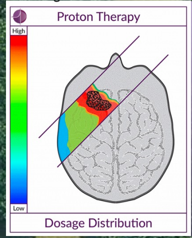
BELLA-PW
40 Joule in 40fs (1 PW @ 1Hz)
- multi-GigaVolt e- acceleration
- Medium-intensity p+ acceleration

BELLA-HTT
3 Joule in 30fs (100 TW @ 5Hz)
- Mono-chromatic gamma rays
- Pump-probe X-rays
- Medium-intensity p+ acceleration

Future kBELLA: 100TW, operation at 1kHz

BELLA FIBER
100s mJ in <100fs (>1kHz)
- Laser R&D
- Light sources at >1kHz

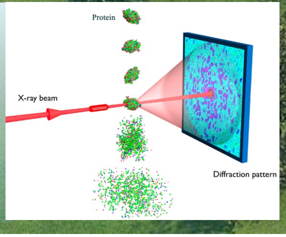




BELLA-IP2 at BELLA-PW
40 Joule in 40fs (1 PW @ 1Hz)
- High-intensity p+ acceleration
- Strong-field physics

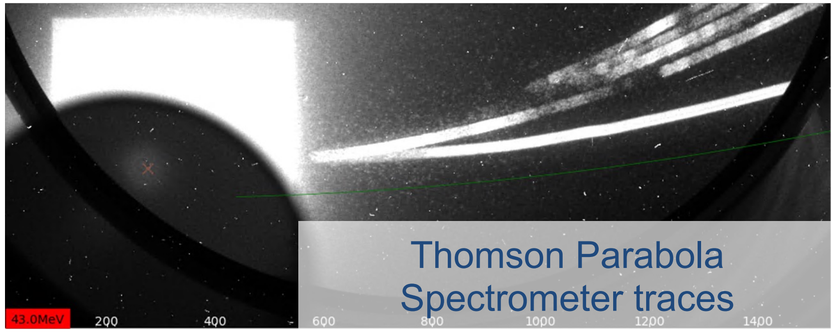
1TW-kHz
4mJ Joule in 4fs (1 TW @ 1kHz)
- Few-MeV electrons & X-rays

BELLA-HTU, 3 Joule in 30fs (100 TW @ 5Hz)
- Electron transport line
- Undulator X-rays



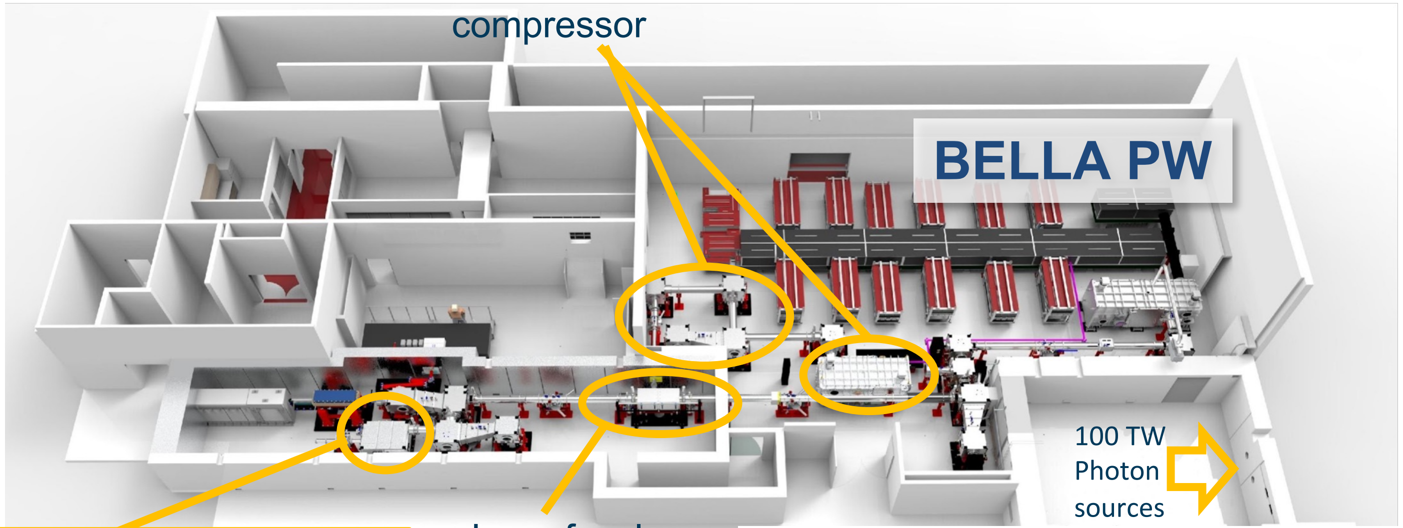
BELLA IP2: new short focal length beamline at the BELLA PW 1 Hz laser to generate ultrahigh laser intensities on target for ion acceleration

Successful commissioning of new IP2 beamline with protons accelerated up to > 40 MeV at 15 J laser pulse energy



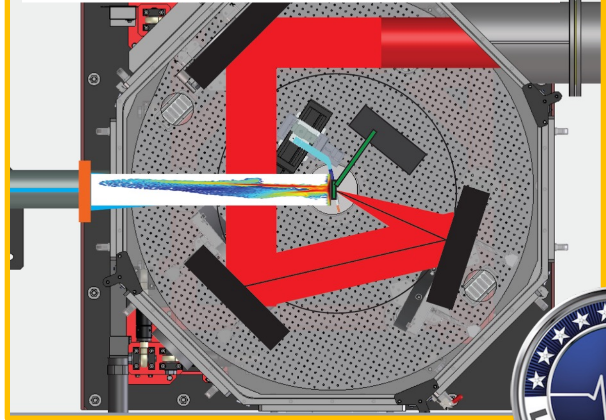
Thomson Parabola Spectrometer traces

New 2nd beamline and vacuum compressor



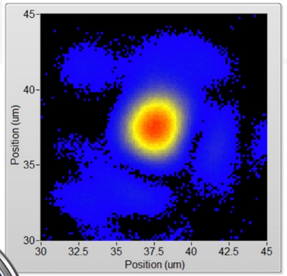
Long focal length TC

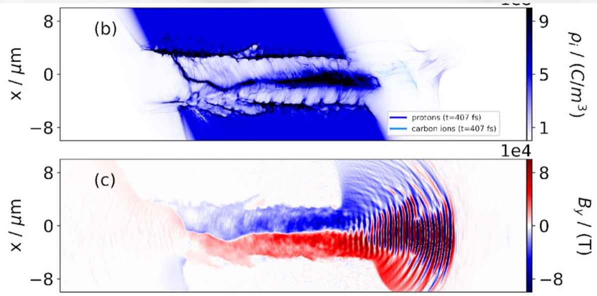
Short focal length F/2.5 OAP



- Proton and ion beams suitable for
  - Fast ignition studies
  - High energy density science
  - R&D on rep-rated 1 Hz targets and diagnostics
  - Radiography, medical applications, etc.

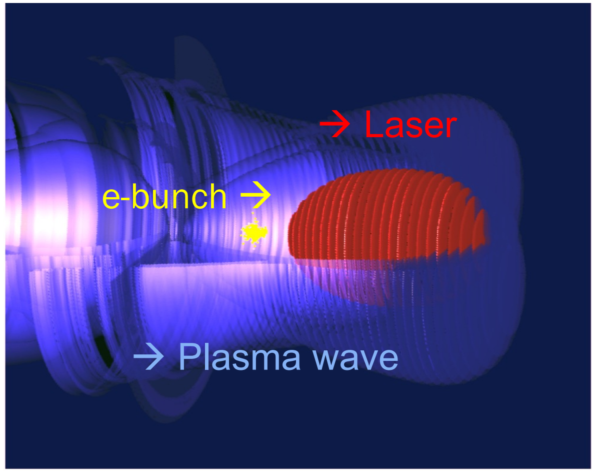
Focal spot measurements indicate > 5 x 10^{21} W/cm^2 can be reached allowing for exiting new plasma regimes to be explored



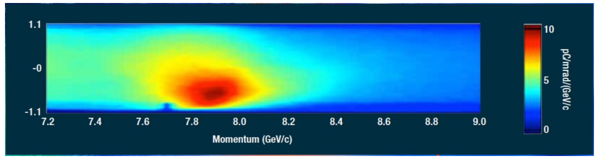


Ultrafast probes from laser-plasma sources of particles and photons

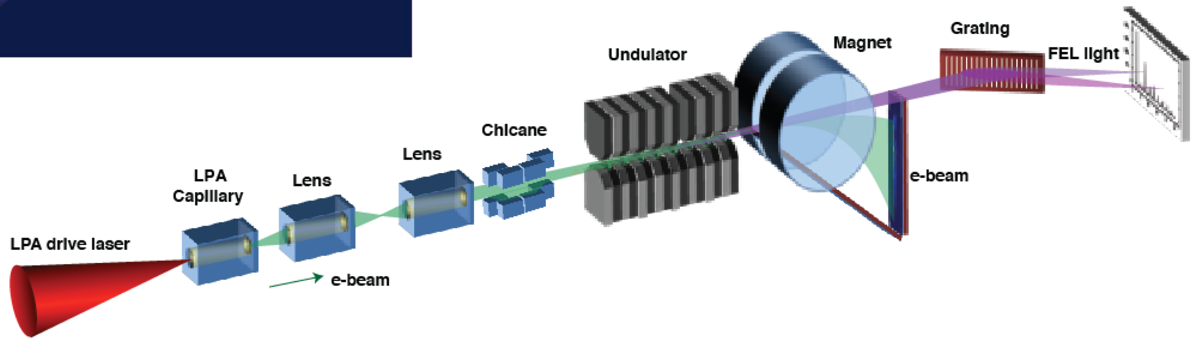
- Laser plasma acceleration of electrons
  - Intrinsically short (10 fs), up to 8 GeV
- Betatron radiation
  - Transverse electron oscillations
  - Broadband width incoherent hard x-rays
- LPA-driven Free Electron Laser
  - Requires very high e-beam quality
  - Coherent soft x-rays
- Thomson scattering
  - Scatter laser off LPA e-beam
  - Narrow bandwidth MeV photons

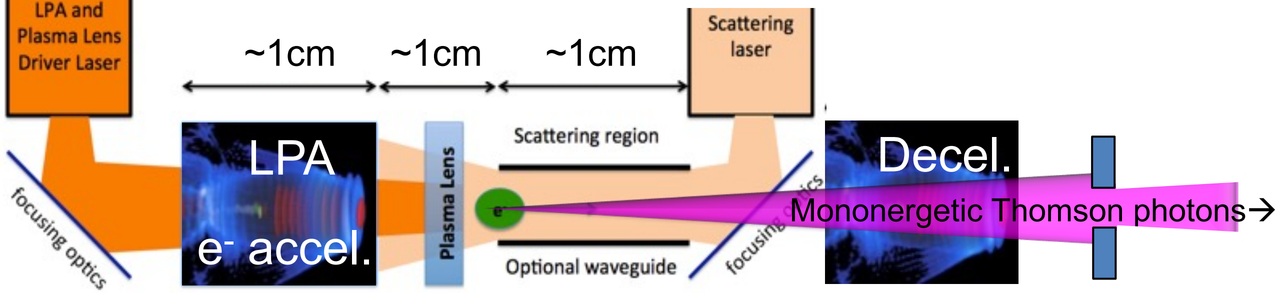


2019: 8 GeV record



in a 20 cm plasma





Feasibility of fiber lasers for laser fusion

A. Galvanauskas[1], T. Zhou[2], A. Rainville[1], C. Pasquale[1], M. Whittlesey[1], Y. Jing[1], R. Wilcox[2], Q. Du[2], J. van Tilborg[2], E. Esarey[2], C. Geddes[2]

(1) University of Michigan, G. Mourou Center for Ultrafast Optical Sciences (2) Lawrence Berkeley National Laboratory, Accelerator Technology and Applied Physics Division

Challenge/Opportunity

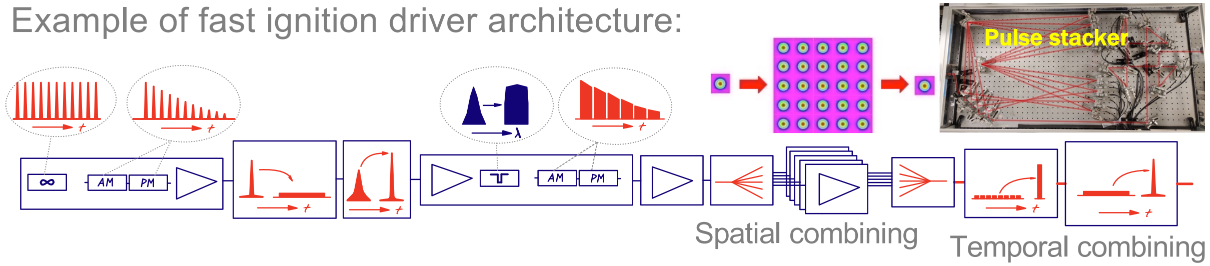
- ➢ Fusion laser driver needs high wall-plug efficiency and high-power capability
- ➢ Fiber lasers are the most efficient high power laser demonstrated so far
- ➢ Combined fiber laser arrays are scalable in pulse energy and average power

Commercial (IPG)100kW CW fiber laser with 35% WPE integrating ~10^2 channels

Approach

- Incoherent/Coherent combining of many fiber laser channels to reach the pulse energies needed for inertial fusion/fast ignition
- Advances in specialty large-core fiber amplifiers could enable ~100mJ per fiber (for fast ignition), and ~1J per multicore fiber (for inertial fusion)
- Laser drivers would require $10^4 – 10^5$ parallel channels, which could be feasible due to fiber compatibility with monolithic integration

Example of fast ignition driver architecture:



Timeliness

Why now?

- Commercial high power multi-modular fiber laser systems
- Recent advances in high energy generation with specialty large core fiber technologies
- Recent advances in coherent combining of ultrashort pulse fiber lasers

R&D goals (e.g. 5 years):

- Large core specialty fiber based integrated amplifier array technology with 0.1-1J per channel
- Pulsed pumping for 30-40% wall-plug efficiency at low rep-rate (~10Hz)
- Specifically for fast ignition: Coherent control of large numbers of fiber channels, and high fidelity temporal pulse stacking

Impact

A pathway to efficient fusion driver laser technology for future IFE plants

Wrapup

- LBNL will be a key contributor to the rapid development of fusion energy, with national, international and commercial investment

- Strong potential for growth in priority areas addressing fusion Long Range Plan
  - Magnet and fusion R&D
  - Inertial fusion ignition physics, drivers
  - Exascale computing
  - Related: LaserNetUS, High Energy Density Physics, Quantum programs

- Leverage context of excellence in Materials, Controls, Lasers, Accelerators, Magnets, Engineering, and Quantum across divisions at LBNL and at UC Berkeley

- Per FY2020 Guidance, LBNL added Plasma and Fusion Energy Sciences as an emerging capability in the Annual Lab Plan; consider Core capability